Introducing the Greenhouse Effect

EES 3310/5310

Global Climate Change

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Class #4: Monday, Feb. 1 2021

Basic Principles from Friday

- **Steady temperature means:**
  - $\text{Heat}_\text{out} = \text{Heat}_\text{in}$
- **Heat in:**
  - Sunlight (**shortwave**)
  - Does not depend on temperature
- **Heat out:**
  - Emitted radiation (**longwave**)
  - Depends on temperature
- If $\text{Heat}_\text{out} \neq \text{Heat}_\text{in}$,
  - Temperature rises or falls until
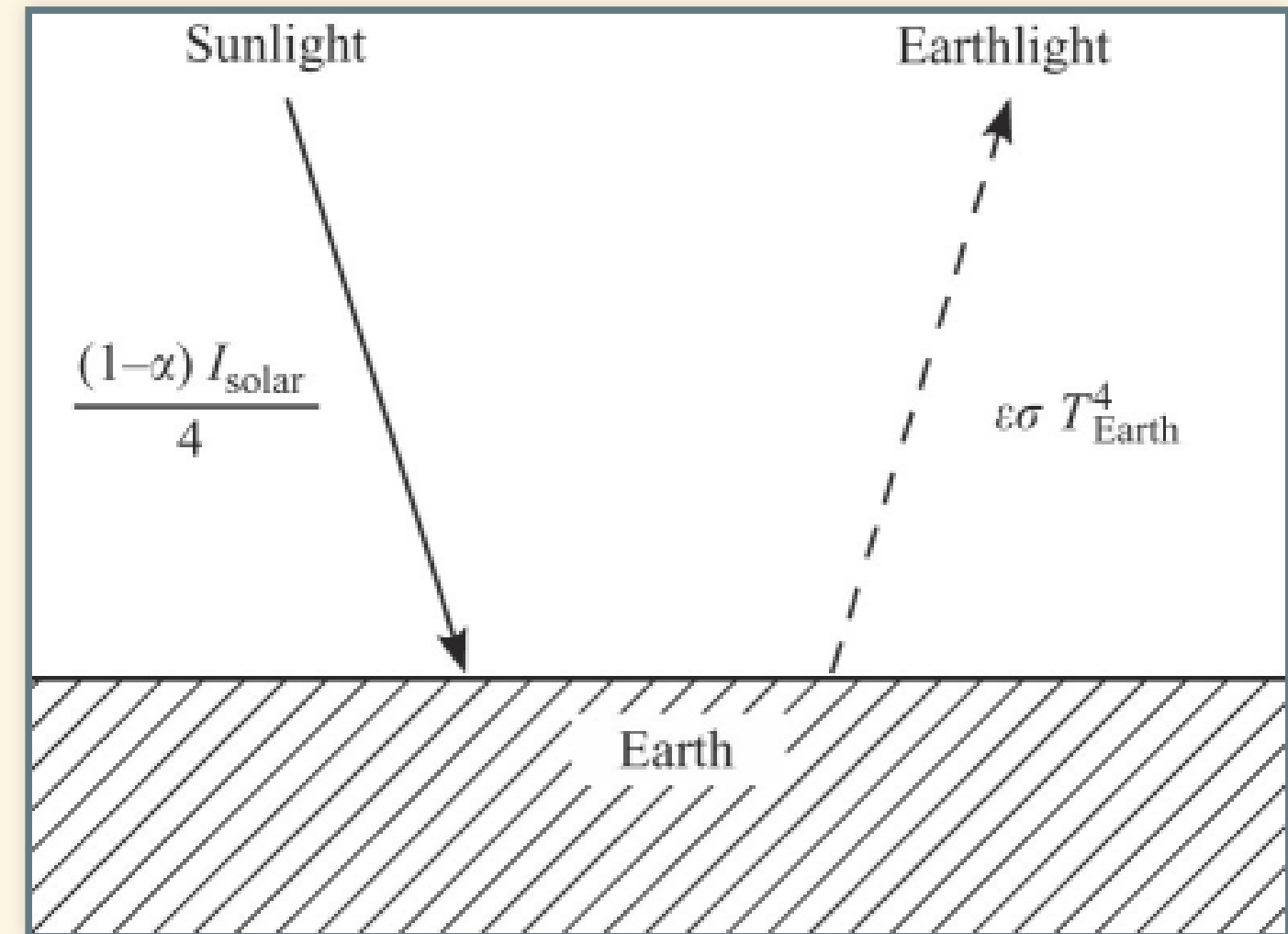
$$\text{Heat}_\text{out} = \text{Heat}_\text{in}$$

Temperature of the Earth

Bare-Rock Model: No Atmosphere

Sunlight

Earthlight

$$\frac{(1-\alpha)\, I_{\text{solar}}}{4}$$

$$\varepsilon\sigma\, T^4_{\text{Earth}}$$
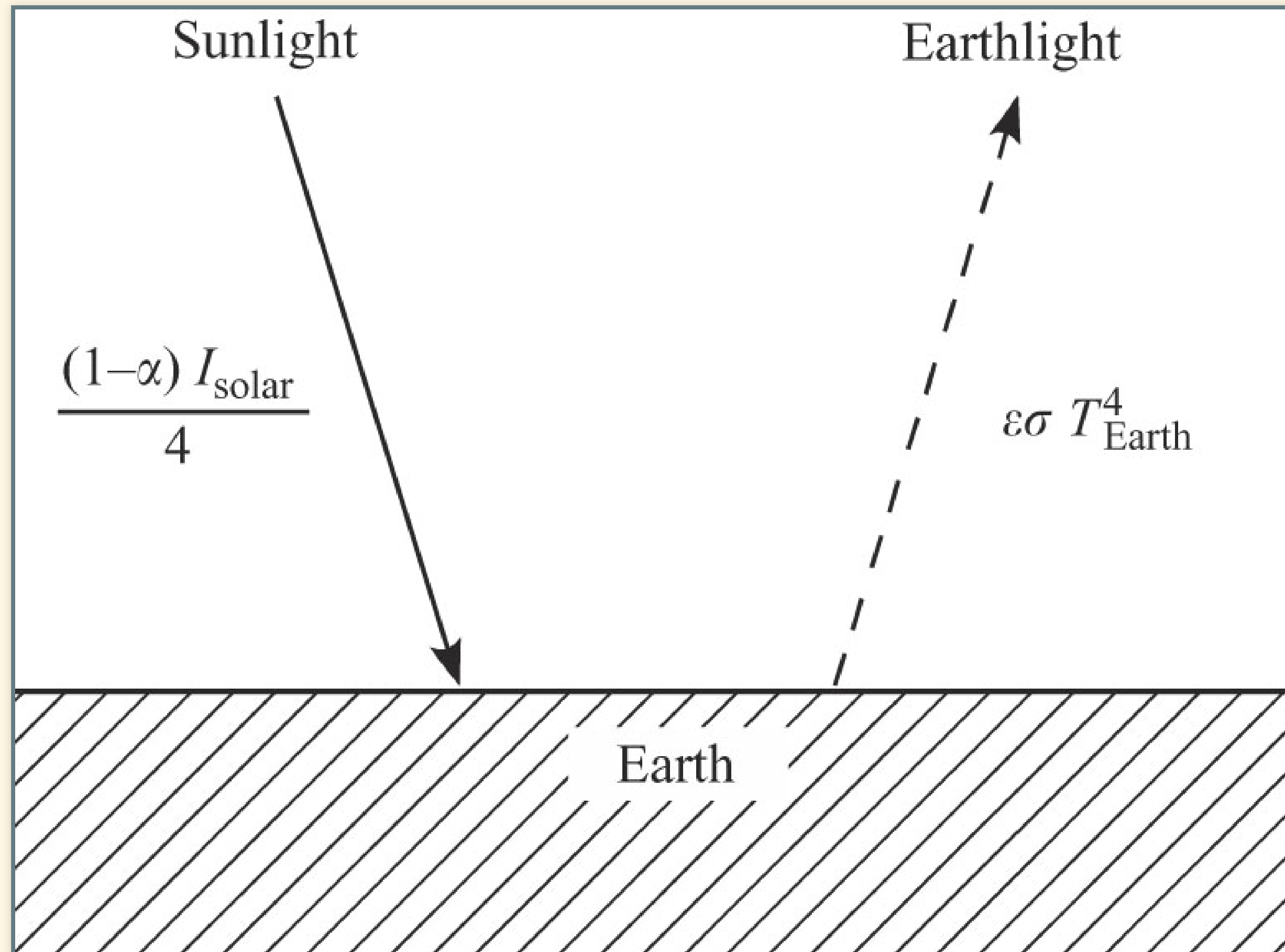
Earth

A subtle point...

- Emissivity ε is fraction absorbed

- Albedo α is fraction reflected

- For an opaque surface, $\alpha + \varepsilon = 1$

- So how is $\alpha = 0.30$ and $\varepsilon = 1.00$?

- α & ε are different for shortwave & longwave.

- Shortwave: $\alpha = 0.30$, $\varepsilon = 0.70$

- Longwave: $\alpha = 0.00$, $\varepsilon = 1.00$

Sunlight   Earthlight

$\frac{(1-\alpha)\,I_{\text{solar}}}{4}$

$\varepsilon\sigma\,T_{\text{Earth}}^4$

Earth

Temperature of Earth (Bare Rock Model)

1. $F_{\text{out}} = F_{\text{in}}$ (Heat flux balances)

2. On average,

$$F_{\text{in}} = \frac{(1 - \alpha)}{4} I_{\text{solar}}$$

3. $F_{\text{out}} = \varepsilon \sigma T^4$.

4. Solve for T:

$$T = \sqrt[4]{\frac{(1 - \alpha)I_{\text{solar}}}{4\varepsilon\sigma}}$$

$I_{\text{solar}} = 1350 \, \text{W}/\text{m}^2$
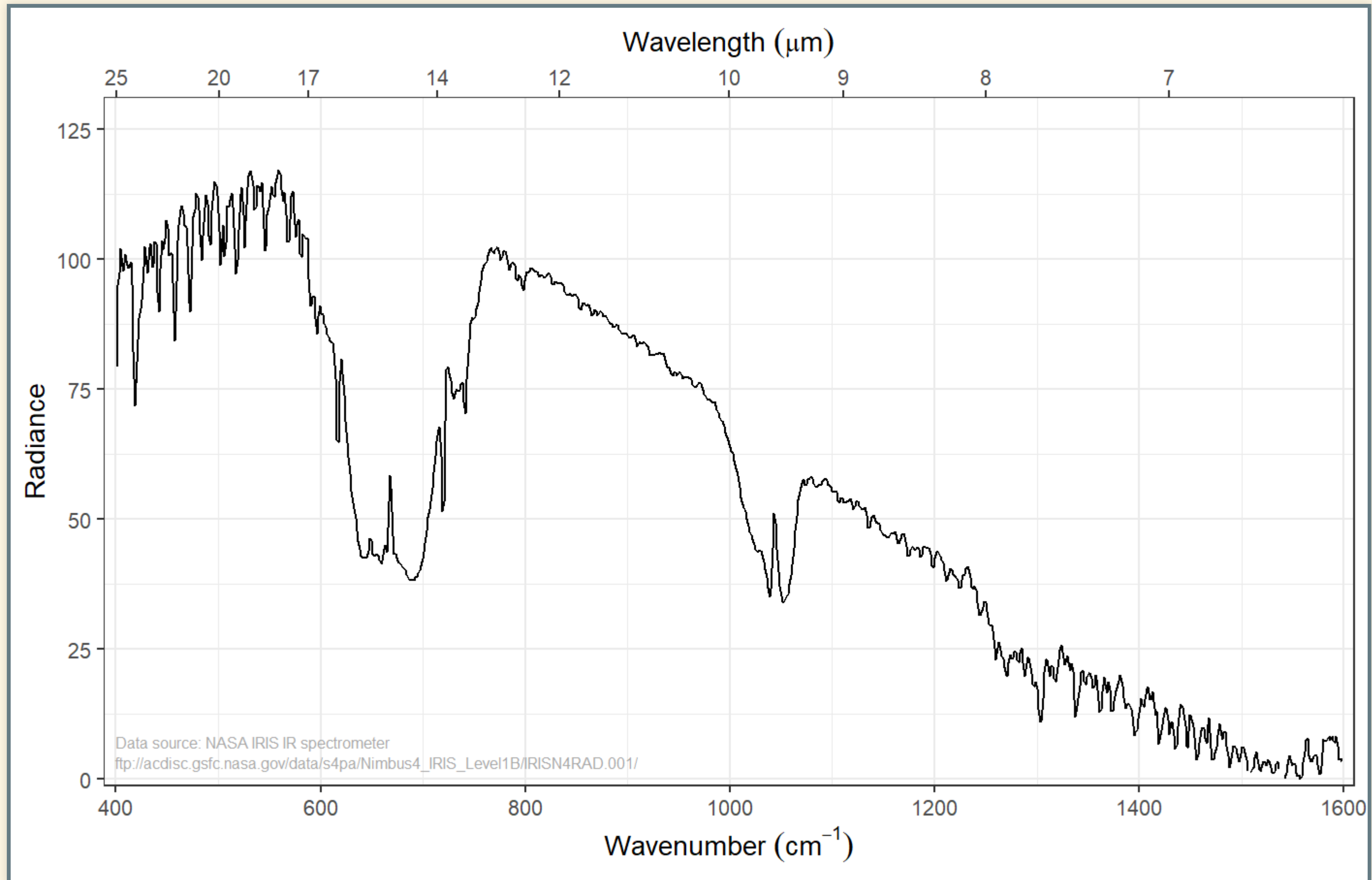
$\alpha = 0.30$

$\varepsilon = 1$

$\sigma = 5.67 \times 10^{-8} \, \text{W}\,\text{m}^{-2}\,\text{K}^{-4}$

$T = 254 \, \text{K} = -19 \, °\text{C} = -2 \, °\text{F}$

Terrestrial Planets

	Earth	**Mars**	**Venus**
Distance from sun	1 AU	1.5 AU	0.72 AU
$1/\mathrm{Distance}^2$	1.00	0.44	1.9
Solar constant	$1350 \mathrm{\ W/m}^2$	$600 \mathrm{\ W/m}^2$	$2604 \mathrm{\ W/m}^2$
Albedo	0.30	0.17	0.71
$T_{\mathrm{bare\ rock}}$	$254 \mathrm{\ K}\ (-2\,^\circ\mathrm{F})$	$216 \mathrm{\ K}\ (-70\,^\circ\mathrm{F})$	$240 \mathrm{\ K}\ (-27\,^\circ\mathrm{F})$
T_{surface}	$295 \mathrm{\ K}\ (71\,^\circ\mathrm{F})$	$240 \mathrm{\ K}\ (-28\,^\circ\mathrm{F})$	$700 \mathrm{\ K}\ (800\,^\circ\mathrm{F})$
Δ_T	$41 \mathrm{\ K}\ (74\,^\circ\mathrm{F})$	$24 \mathrm{\ K}\ (42\,^\circ\mathrm{F})$	$460 \mathrm{\ K}\ (828\,^\circ\mathrm{F})$

Oops! We forgot the atmosphere!

Data source: NASA IRIS IR spectrometer
ftp://acdisc.gsfc.nasa.gov/data/s4pa/Nimbus4_IRIS_Level1B/IRISN4RAD.001/

Does Earth look like a blackbody?

Data source: NASA IRIS IR spectrometer
ftp://acdisc.gsfc.nasa.gov/data/s4pa/Nimbus4_IRIS_Level1B/IRISN4RAD.001/

Legend:
- Observed
- 300 K (80 F)
- 280 K (44 F)
- 260 K (8 F)
- 240 K (-28 F)
- 220 K (-64 F)
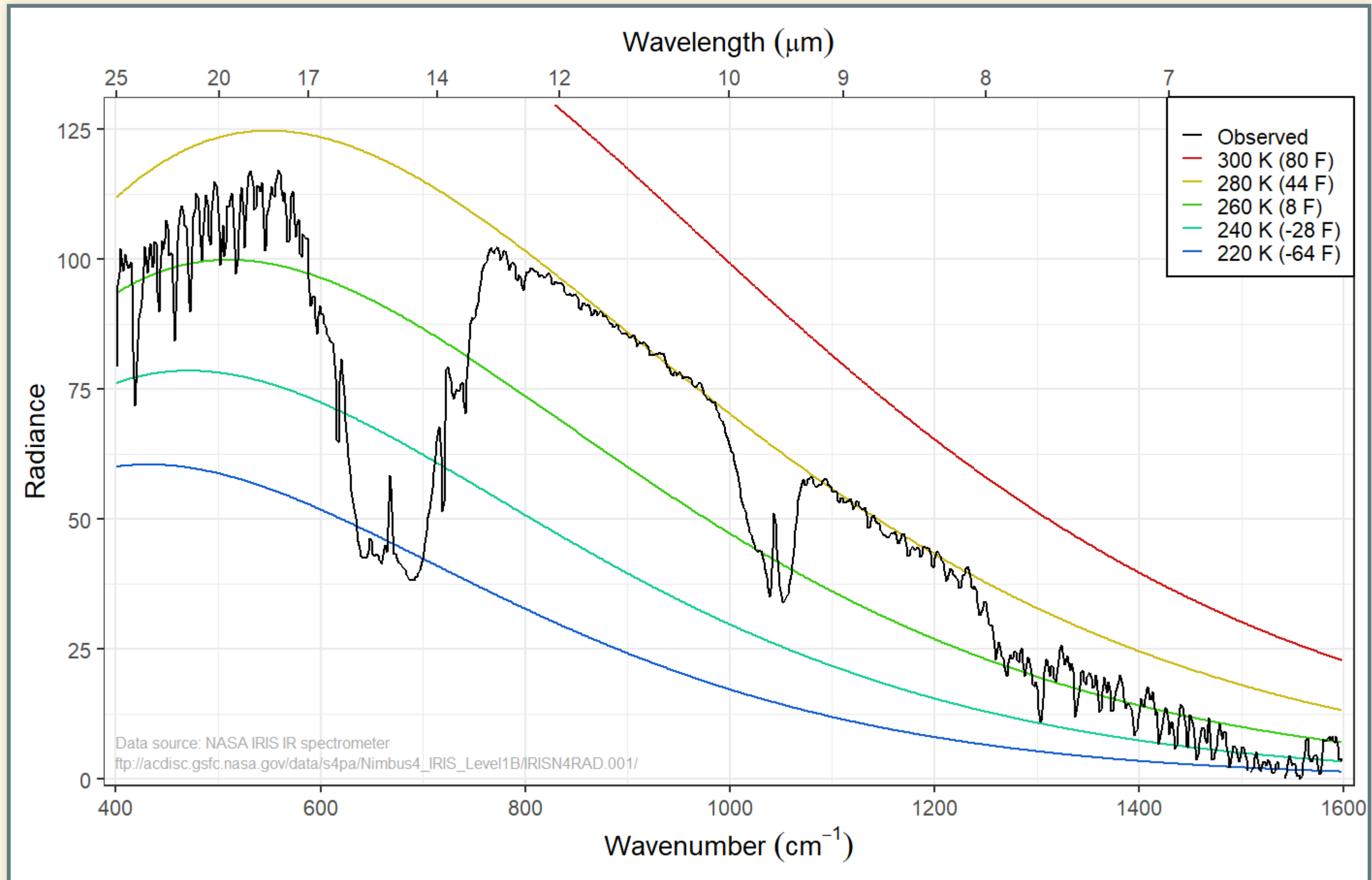
One-Layer Model of the Greenhouse Effect

Layer Model

Sunlight

Longwave (>3 micron, < 3300/cm)   2%
Shortwave (UV + Vis + Near-IR)   98%

Radiation from Sun

Radiation intensity

43%

49%

7%

Radiation emitted from Earth

0.1   0.5   1.0   1.5   2.0   10 20 30 40 50
Wavelength in micrometers

Ultra-violet | Visible | Infrared
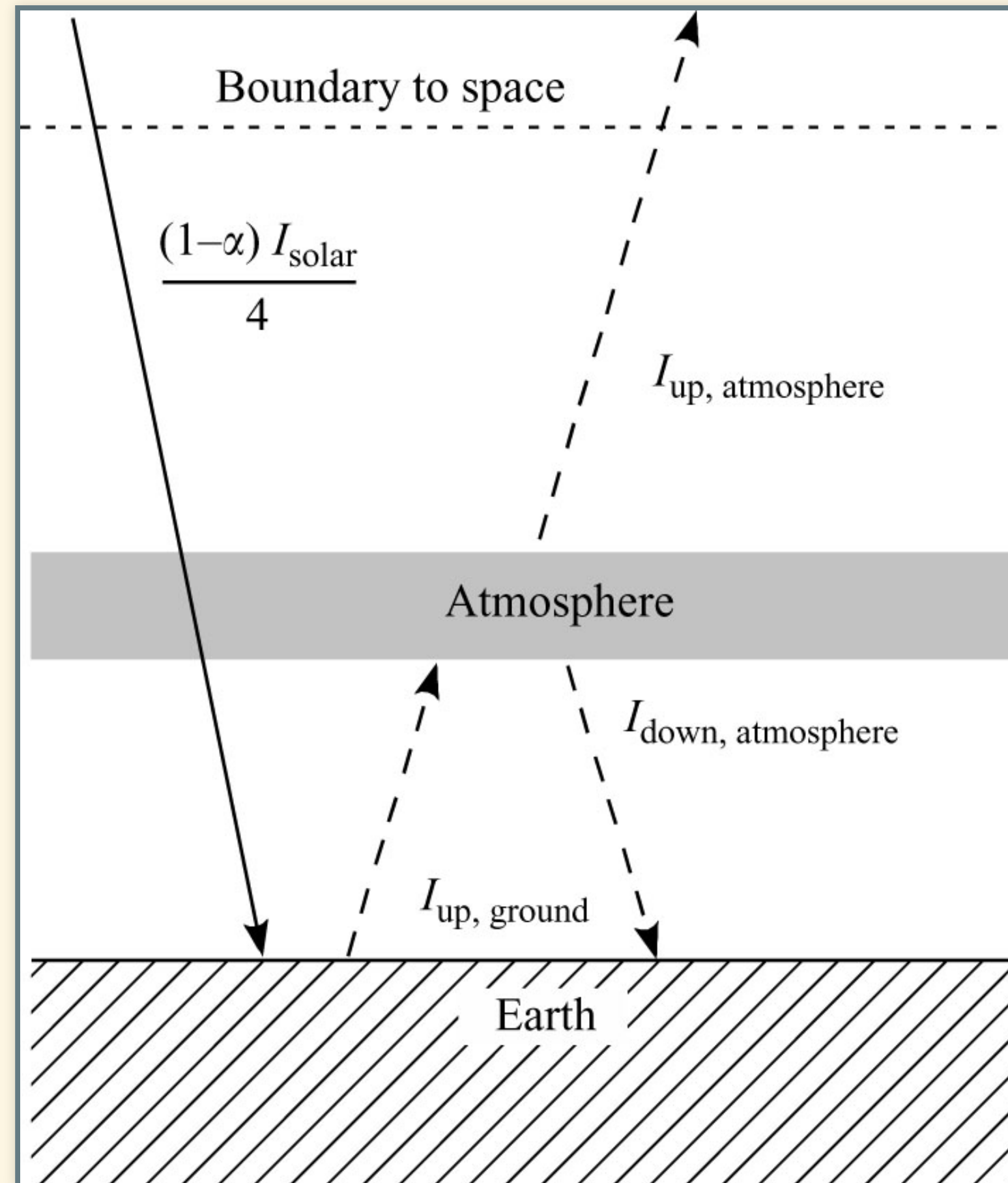
Shortwave   Longwave
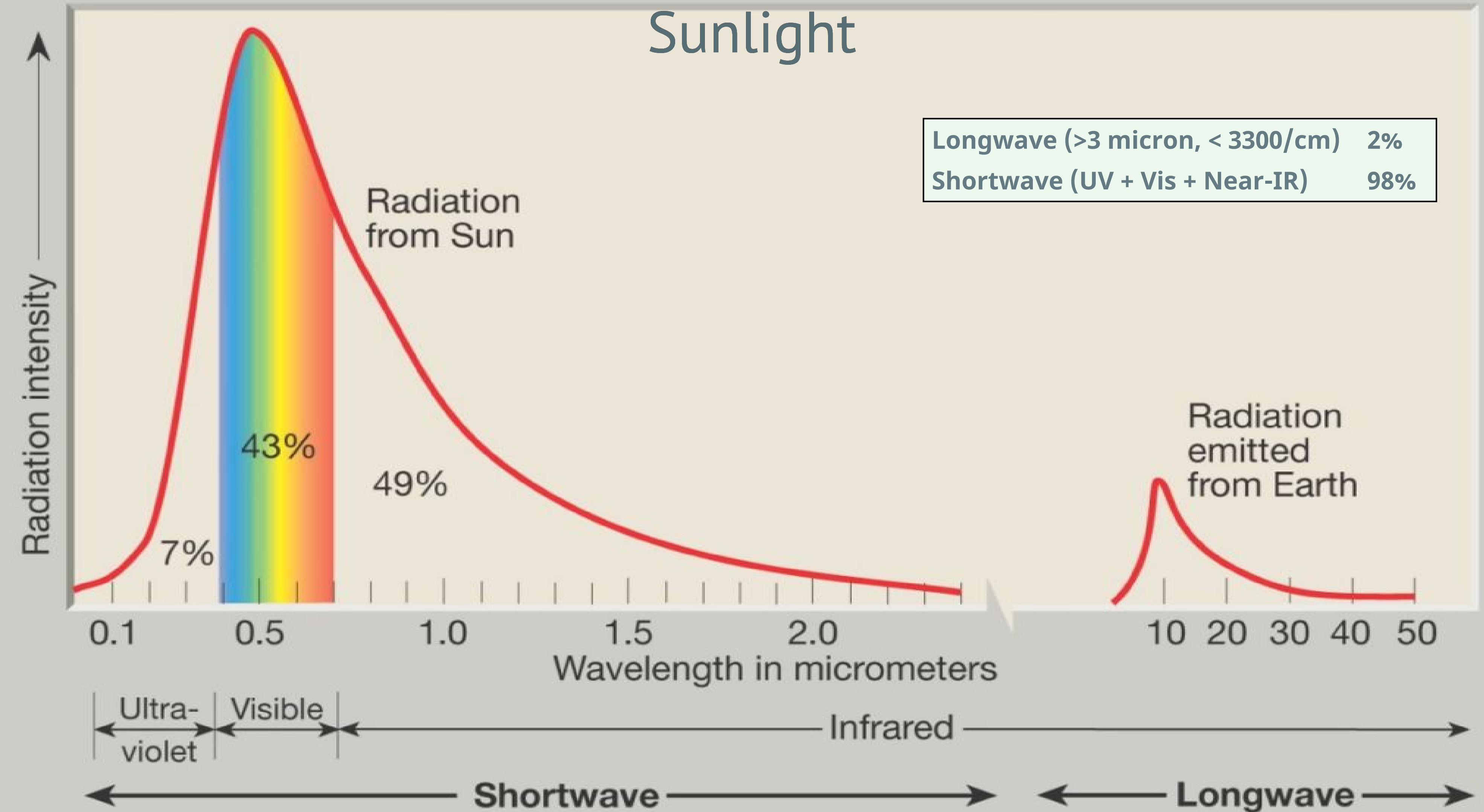
Atmosphere

Make **simplifying assumptions**:

- Perfectly **transparent** to **shortwave** light
  - Like a pane of glass: $\varepsilon = 0$
- Perfectly **opaque** to **longwave** light
  - Like a blackbody: $\varepsilon = 1$

**Anything that
transmits most shortwave
and
absorbs most longwave
is a greenhouse gas**

Balance of energy for earth system

- Always start analyzing from the top down
  - Look at energy balance at the boundary to space, above the top of the atmosphere.
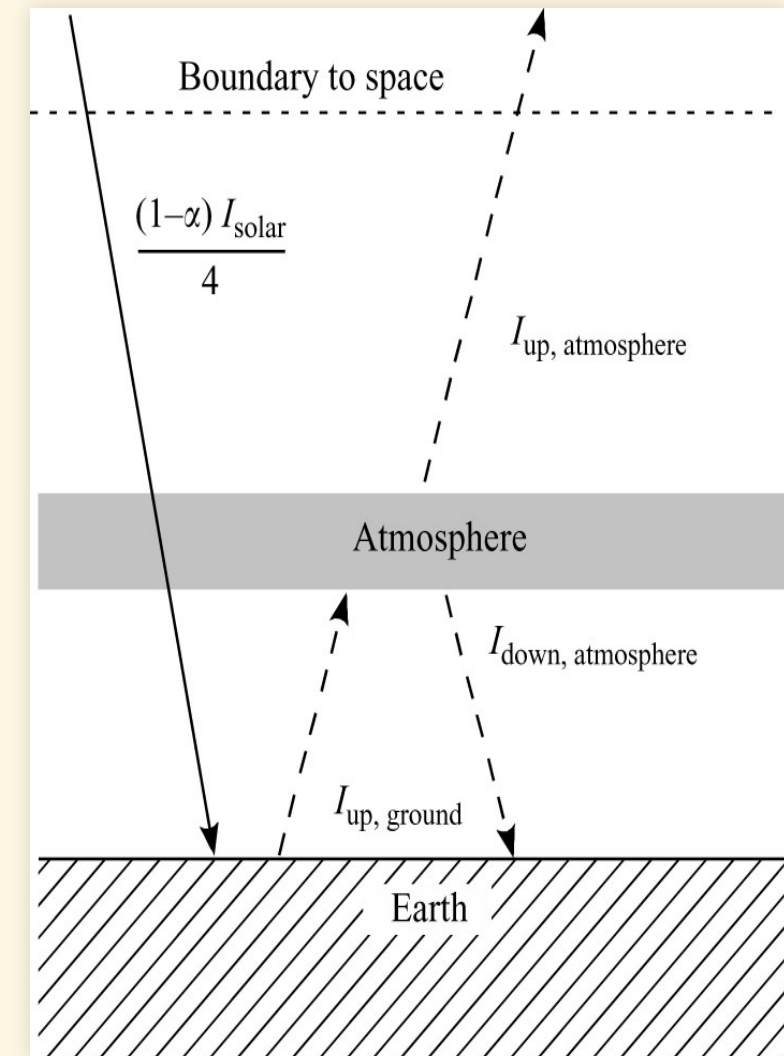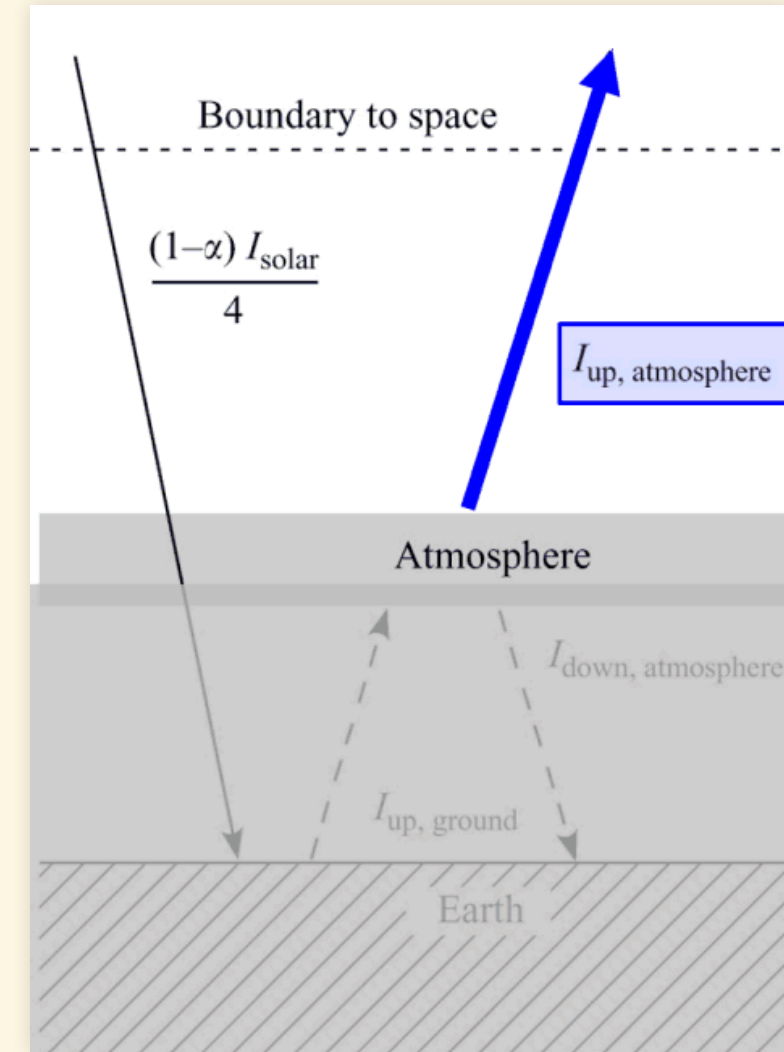
Balance of energy for earth system

- At top of atmosphere: $F_{out} = F_{in}$

$$I_{up,\,atmos} = I_{in} \quad \text{(intensity of absorbed sunlight)}$$

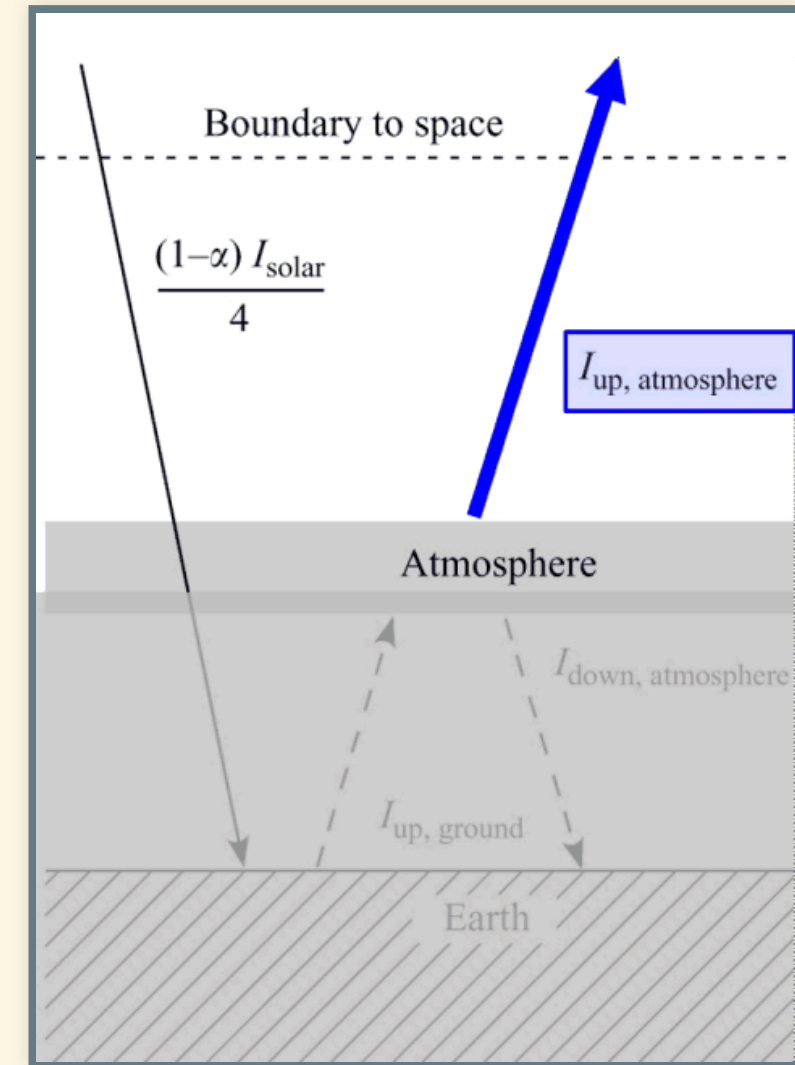$$\varepsilon\sigma T_{atmos}^4 = \frac{(1-\alpha)I_{solar}}{4}$$

- Aha! We can find T_{atmos}!

$$T_{atmos} = \sqrt[4]{\frac{(1-\alpha)I_{solar}}{4\varepsilon\sigma}}$$

Balance of energy for earth system

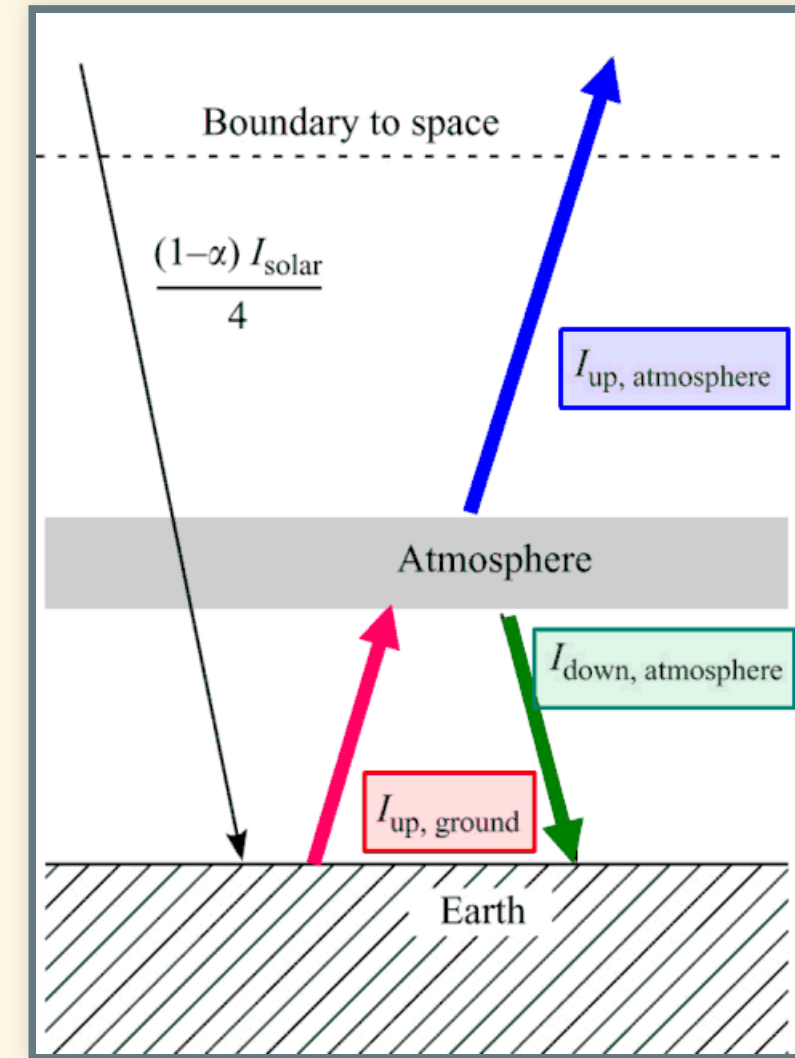$$T_{\text{atmos}} = \sqrt[4]{\frac{(1 - \alpha) I_{\text{solar}}}{4 \varepsilon \sigma}}$$

- Just like bare rock model!
- We call this the **skin temperature**

Boundary to space

$\frac{(1-\alpha) I_{\text{solar}}}{4}$

$I_{\text{up, atmosphere}}$

Atmosphere

$I_{\text{down, atmosphere}}$

$I_{\text{up, ground}}$

Earth

Balance of energy for atmosphere

Atmosphere: $\text{Heat}_\text{in} = \text{Heat}_\text{out}$

$$I_\text{up,ground} = I_\text{up,atm} + I_\text{down,atm}$$
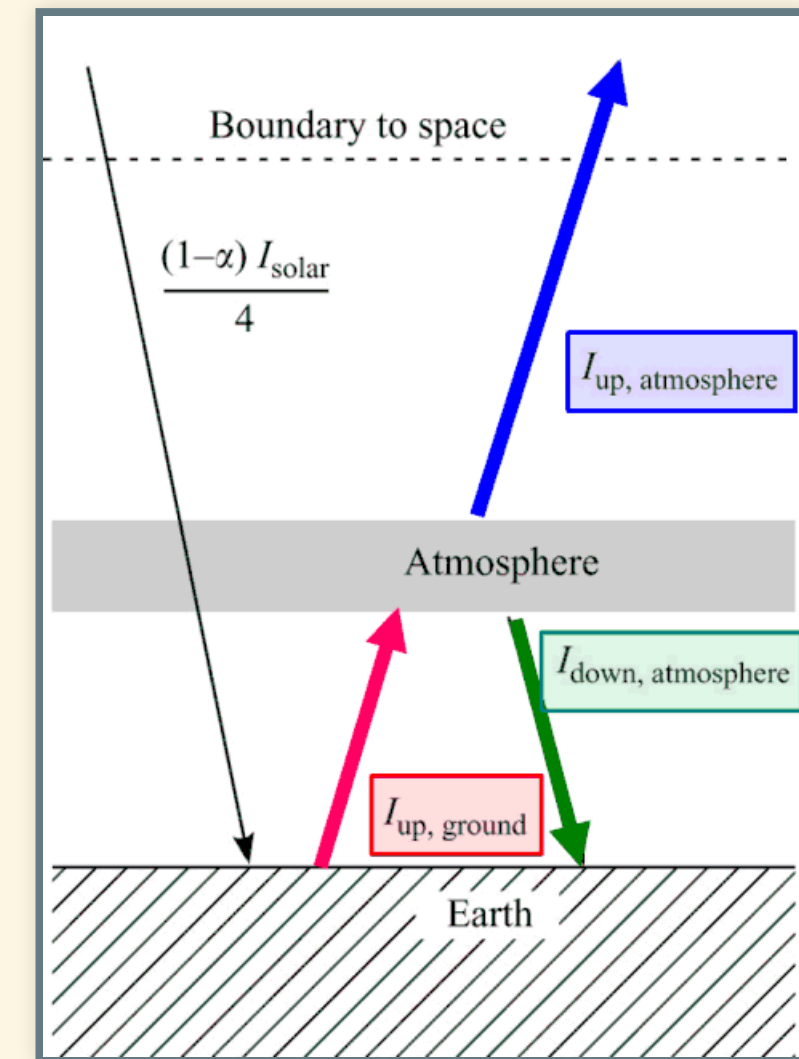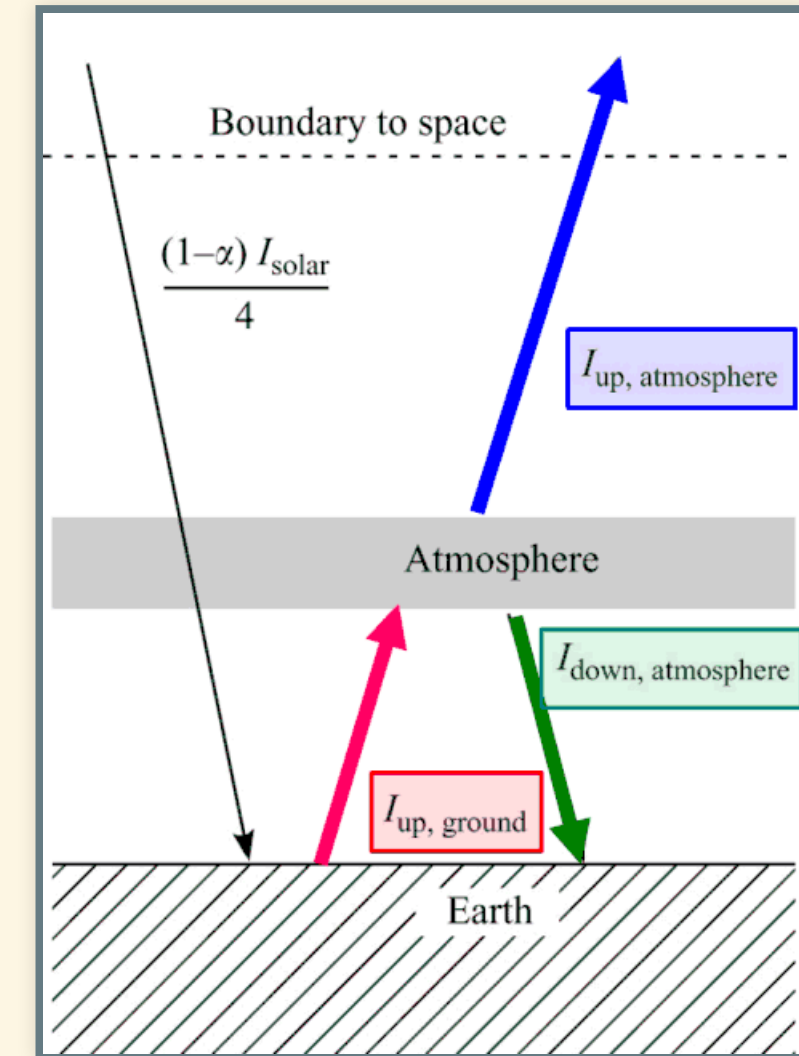
Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon \sigma T_{\text{atm}}^4$$

Boundary to space

$\dfrac{(1-\alpha)\, I_{\text{solar}}}{4}$

$I_{\text{up, atmosphere}}$

Atmosphere

$I_{\text{down, atmosphere}}$

$I_{\text{up, ground}}$

Earth

Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T^4_{\text{atm}}$$

$$I_{\text{up,ground}} = \varepsilon\sigma T^4_{\text{ground}}$$

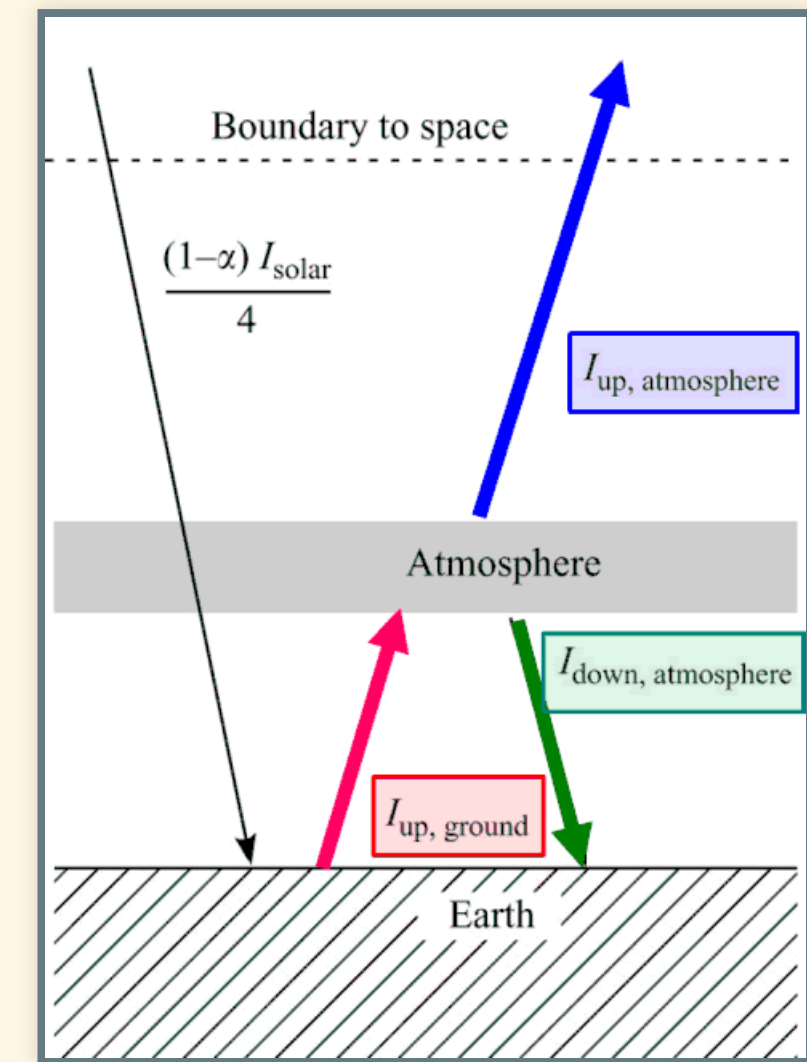# Balance of energy for atmosphere

Atmosphere: heat in = heat out.

$$I_{\text{up,ground}} = I_{\text{up,atm}} + I_{\text{down,atm}}$$

$$I_{\text{up,atm}} = I_{\text{down,atm}} = \varepsilon\sigma T^4_{\text{atm}}$$

$$I_{\text{up,ground}} = \varepsilon\sigma T^4_{\text{ground}}$$

$$\varepsilon\sigma T^4_{\text{ground}} = 2\varepsilon\sigma T^4_{\text{atm}}$$

Boundary to space

$\dfrac{(1-\alpha)\, I_{\text{solar}}}{4}$

$I_{\text{up, atmosphere}}$

Atmosphere

$I_{\text{down, atmosphere}}$

$I_{\text{up, ground}}$

Earth

Principles:

- Start at the top.
- For each layer, $\text{Heat}_{\text{out, up}} = \text{Heat}_{\text{out, down}}$
- Each layer balances $\text{Heat}_{\text{in, total}} = \text{Heat}_{\text{out, total}}$
  - Each layer has uniform temperature:
    - The top and bottom of the layer have the same temperature.
    - So the intensity emitted from the top and bottom is the same.
- The bottom layer of the atmosphere tells us $\text{Heat}_{\text{up, ground}}$
- Get ground temperature from $\text{Heat}_{\text{up, ground}}$

Processing math: 100%
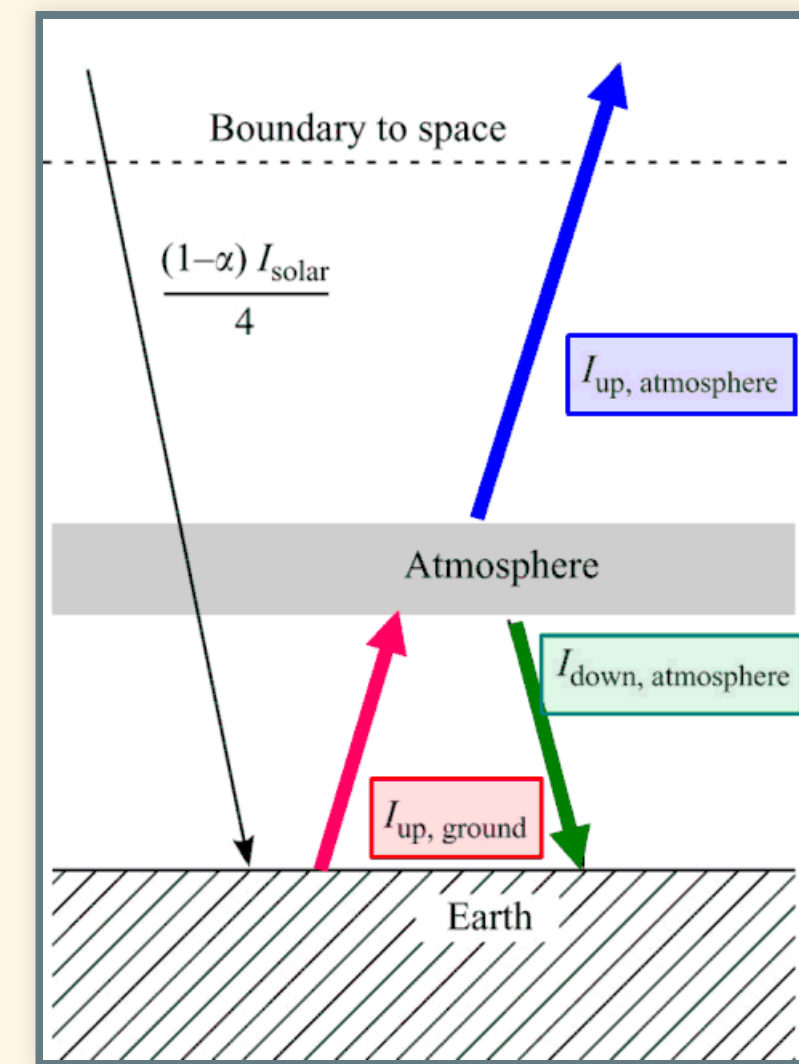
Finish the problem

$$\varepsilon \sigma T^4_{\text{ground}} = 2\varepsilon \sigma T^4_{\text{atm}}$$

$$T^4_{\text{ground}} = 2 T^4_{\text{atm}}$$

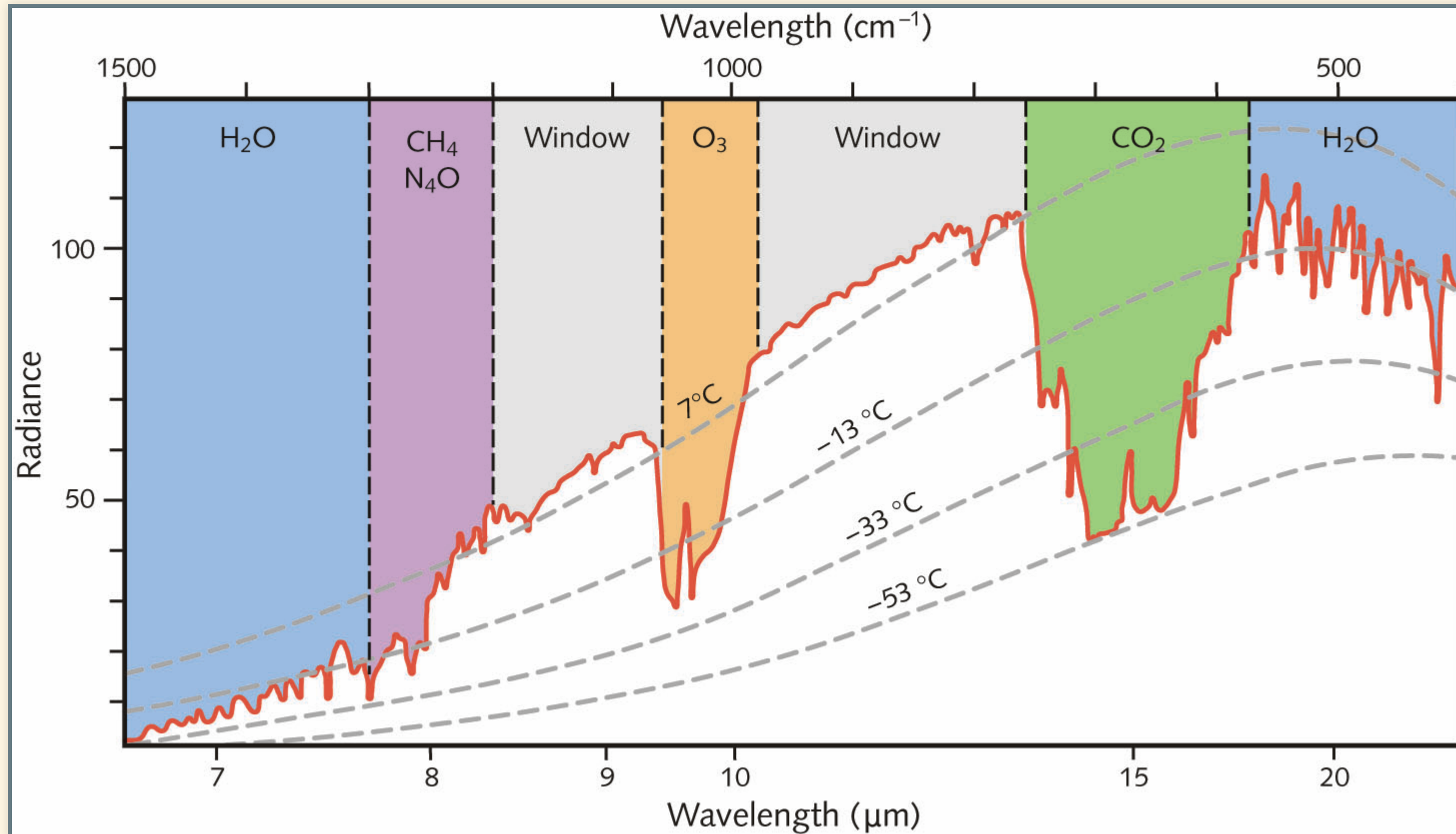$$T_{\text{ground}} = \sqrt[4]{2}\, T_{\text{atm}}$$

$$= 1.19 T_{\text{atm}}$$

- Skin temp: $T_{\text{atm}} = T_{\text{skin}} = T_{\text{bare rock}} = 254\ K$

- Ground temp (1-layer): $T_{\text{ground}} = \sqrt[4]{2} T_{\text{atm}} = 302\ K$

- Difference: Greenhouse effect $= 48\ K$

  Note: These numbers are slightly different from what's in the book. Don't worry about that.

Boundary to space

$\dfrac{(1-\alpha)\, I_{\text{solar}}}{4}$

$I_{\text{up, atmosphere}}$

Atmosphere

$I_{\text{down, atmosphere}}$
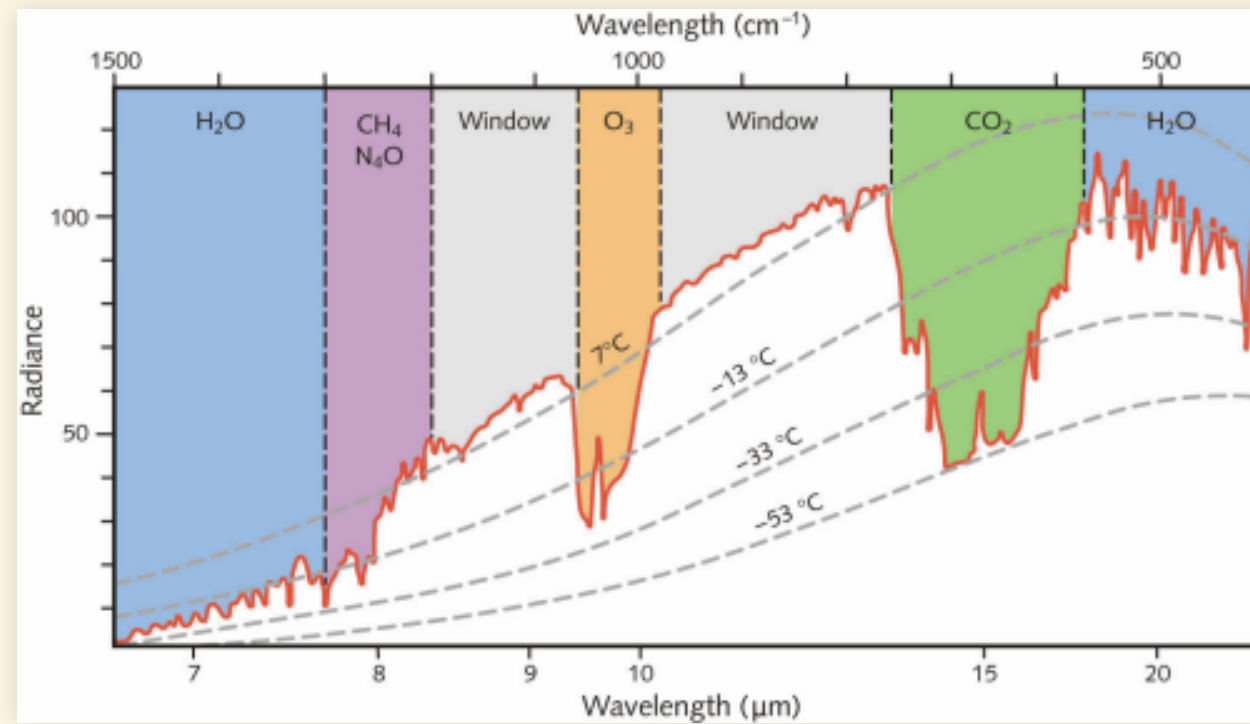
$I_{\text{up, ground}}$

Earth

Greenhouse Gases

Greenhouse Gases

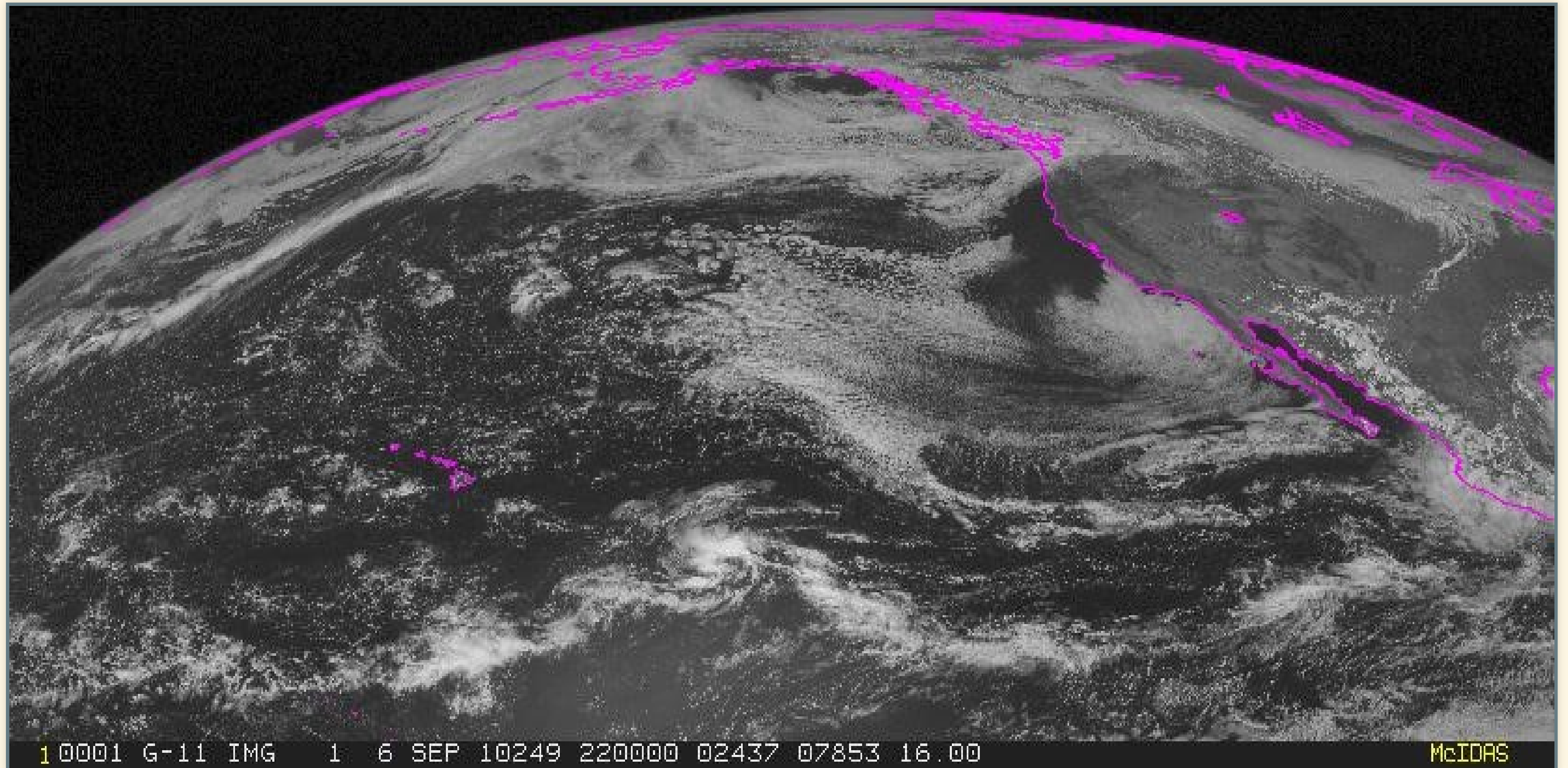# Greenhouse Gases

- Brightness: Stefan-Boltzmann law:
  - $I = \varepsilon\sigma T^4$
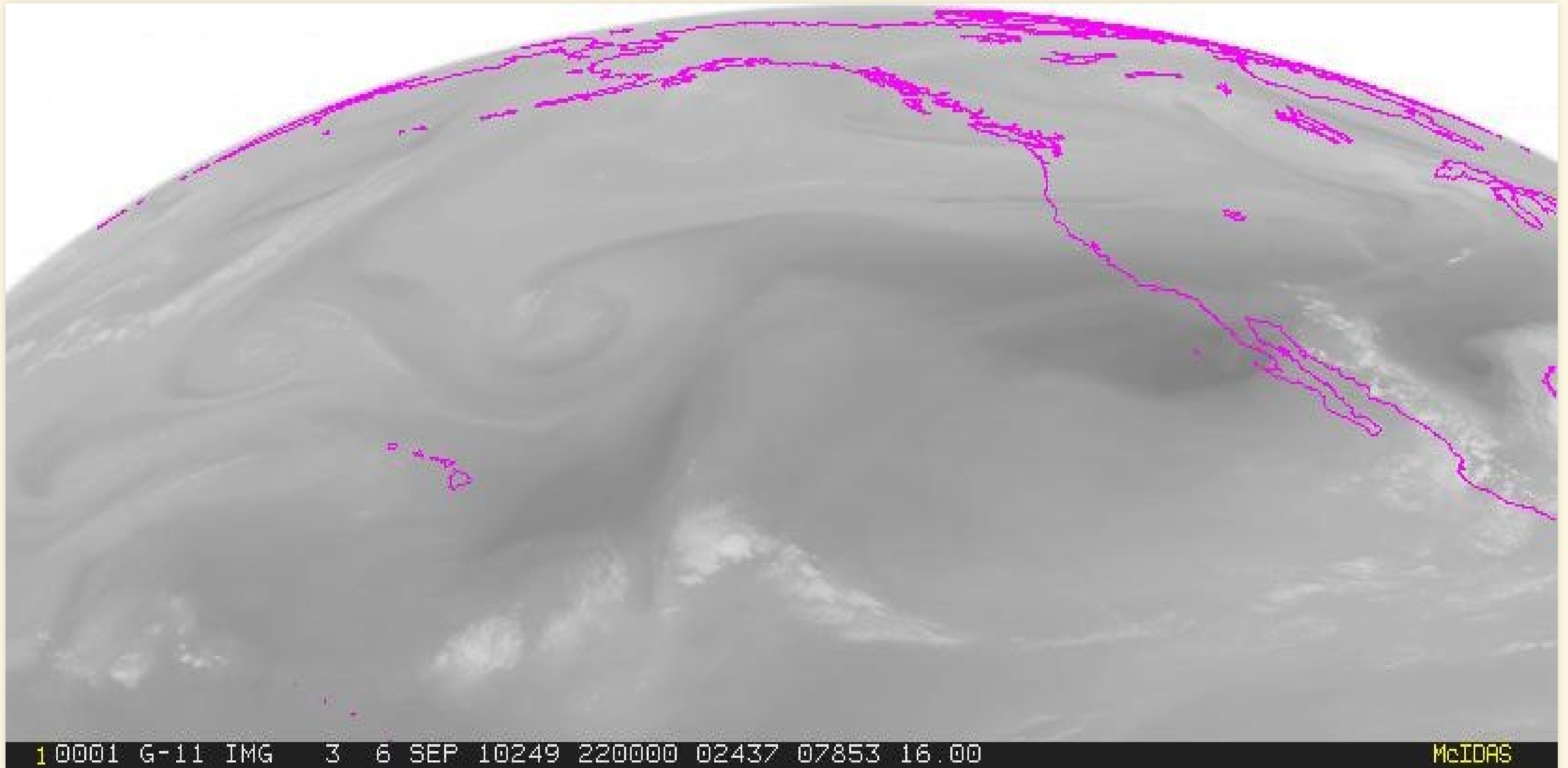 - $\varepsilon = 1$

- Brighter = Hotter
- Hotter = closer to ground
  - Satellite can see through atmosphere to low altitude (hot, bright) in "window" region.
  - Satellite can see to middle-troposphere (cold, dimmer) in "water vapor" region
  - Satellite can't see past top of troposphere (very cold, very dim) in CO_2 region.

2

Earth Seen by Satellites

Visible

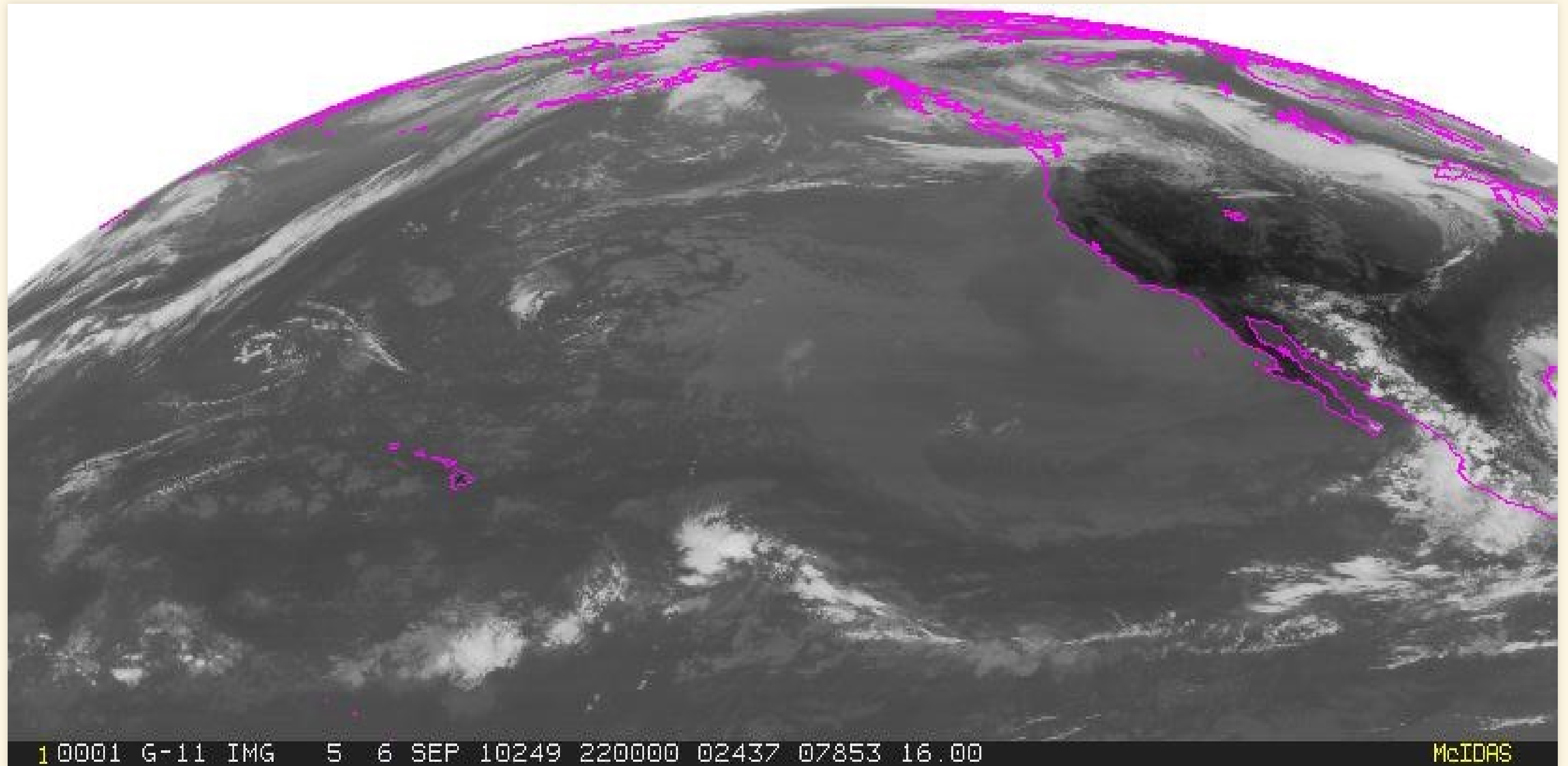# 6.8 μm (Water Vapor)

10001 G-11 IMG   3   6 SEP 10249 220000 02437 07853 16.00   McIDAS

Processing math: 100%

12.0 μm (Window)

10001 G-11 IMG   5   6 SEP 10249 220000 02437 07853 16.00   McIDAS

Water, Window, Visible
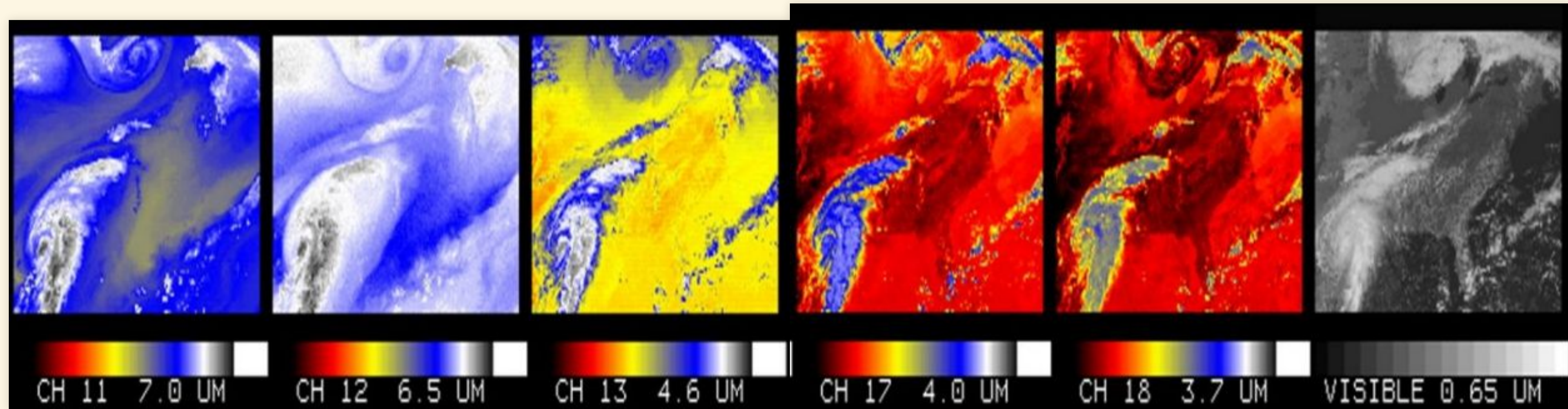
CO$_2$ peak vs. Window

Terrestrial Planets

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	$1350 \ \mathrm{W/m}^2$	$600 \ \mathrm{W/m}^2$	$2604 \ \mathrm{W/m}^2$
Albedo	0.30	0.17	0.71
$T_{\mathrm{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K

Vocabulary note:

- "radiative temperature"
- "skin temperature"
- "bare rock temperature"

all mean the same thing.

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	$1350 \ \mathrm{W/m^2}$	$600 \ \mathrm{W/m^2}$	$2604 \ \mathrm{W/m^2}$
Albedo	0.30	0.17	0.71
$T_{\mathrm{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K
Difference	7 K	17 K	-414 K

One-layer model works pretty well for Earth.

Not so well for Mars

Terribly for Venus.

Earth, Mars, Venus

	Earth	Mars	Venus
Solar constant	$1350 \ \text{W}/\text{m}^2$	$600 \ \text{W}/\text{m}^2$	$2604 \ \text{W}/\text{m}^2$
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$T_{\text{radiative}}$	254 K	216 K	240 K
Actual T_{surface}	295 K	240 K	700 K
One-Layer T_{surface}	302 K	257 K	286 K
Difference	7 K	17 K	−414 K
Atmospheric pressure at surface	1013 mb	6 mb	92,000 mb